
ACTIVE MEMBER DESIGN, MODELING, AND VERIFICATION

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ABSTRACT

The design and development of active members intended for use in structural control applications is presented. The use of three different solid state actuation materials, namely, **piezoelectric**, **electrostrictive**, and **magnetostriuctive**, is discussed. Test data is given in order to illustrate the actuator and device characteristics and performance.

1. INTRODUCTION

The investigation and use of active materials for structural control applications has grown in recent years. The Jet Propulsion Laboratory (JPL) has focused mainly on developing in-line actuators, also known as active members, mounted in a truss or a truss-like structure for fine-scale positioning and vibration control purposes. Additionally, other research programs such as MIT's, VPI's, TRW's, McDonnell Douglas', etc. have studied the use of various materials for in-line actuators. One result of these technology programs is that solid state actuation technology is beginning to make the transition from a research commodity to an advanced technology flight project equipment. The advanced technology flight project use of solid state actuators is exemplified, at JPL, by the articulating fold mirrors (AFM's) on the Wide Field/Planetary Camera II that will be installed on the Hubble Space Telescope in late '93 (Fanson and Ealey, 1993), and the cryo-cooler motion suppression experiment (Glaser, 1992). With the proliferation of in-line actuators, it becomes useful to catalog the available materials based on performance and design goals.

The materials investigated under the JPL Control Structure Interaction (CSI) and Precision Segmented Reflector (PSR)

programs include **piezoelectric**, **electrostrictive** and **magnetostriuctive** materials. Traditionally, albeit somewhat naively, the performance of these actuators has been evaluated based primarily on the quantities: (1) maximum displacement, (2) maximum blocked force, and (3) gain. The deviation of the actuator response from the ideal behavior is then described by terms such as: hysteresis, creep, and loss tangent.

The JPL CSI and PSR programs have focused on vibration damping in the context of developing technology for micro-precision structures. To date these programs have successfully demonstrated active vibration control on a number of test-beds, namely: CSI Phase O (Fanson, et al, 1991), CSI Phase B (Spanos, et al, 1992), PSR precision truss (Chen and Lurie, 1992), PSR erectable truss (Umland and Chen, 1992), the Air Force reduced gravity experiment (Lawrence, 1990), and the LaRC CSI Evolutionary Model (Neat, 1992). The purpose of the CSI program is to develop and demonstrate nanometer level control on a class of precision structures intended for space-based interferometry. The CSI approach to structural quieting is a multi-layer vibration control strategy. Each layer successively removes a portion of vibration disturbance from the system, that is, (1) disturb sources are isolated, (2) the base structure is actively and/or passively damped, and (3) the optical train is isolated from the base structure.

This paper attempts to condense the JPL data on in-line actuators using active materials. Common applications-based design parameters and benchmarks are established and used to measure the performance of the active members in use at JPL. The goal is to provide a database of available material on active members as well as determining what crucial design information is needed.

II. DETERMINING DESIGN CHARACTERISTICS

Active member design requirements are determined by the specific application for which the actuator is intended. At JPL, the applications being developed are positioning and shape control, vibration control, and vibration isolation. These applications can give differing requirements for active member design.

Simple Active Member Model

An ideal mechanical model of an active member is shown in figure 1. Typically, the active member is modeled as an axial structural element, without bending stiffness or damping. The member's stiffness is represented by k_{am} . A force source or actuator is mechanically in parallel with the active member's spring stiffness. The force is given by $k_{am} d_{eff} V$, where d_{eff} is an actuator motor constant that relates the active member's displacement to applied voltage, V is the applied voltage. As will be seen in a later section this type model is appropriate for piezoelectric and electrostrictive based active members, and would have to be slightly modified for a magnetostrictive active member. Two sensors are normally integrated into the active member design, namely: a displacement sensor, and a load sensor. The displacement sensor measures the displacement of one end of the active member relative to the other. The load cell is placed mechanically in series with the active member,

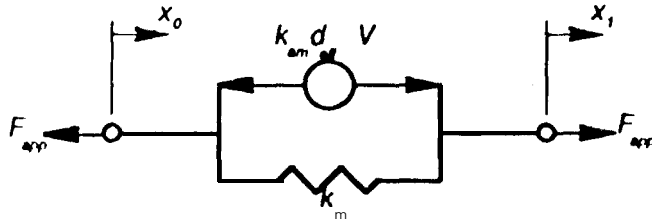


Figure 1: Ideal active member model.

Static Shape Control

The simplest application for an active member or my actuator that can be represented by figure 1, is to position an object or to apply a force against some stiffness. The positioning application is represented in figure 2, where the active member is used to position an object. **Note**, that it is the steady state position that is of interest here. An example of this type of positioning application is the articulated fold mirrors (AFM) that are installed in the Hubble's Wide Field/Planetary Camera II (Fanson and Ealey, 1993). The steady state position of the object, m , in figure 2 is given by

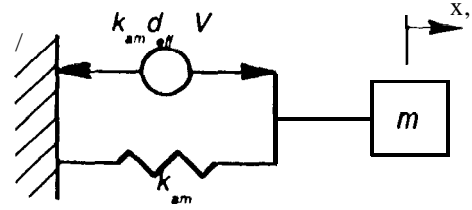


Figure 2: Ideal active member, positioning application.

$$X = \frac{l}{k_{am}} F_{app} + d_{eff} V \quad (1)$$

F_{app} represents an external force, such as the weight of the object being positioned. The accurate positioning of the object is achieved by either an actuator calibration curve, or a focusing an image, etc. The object can also be positioned by a closed loop control system, where V is given by

$$V = -g(x - R) \quad (2)$$

R is the reference displacement, and g is a feedback gain. The closed loop displacement is given by

$$x = \frac{l}{k_{am}(1 + g d_{eff})} F_{app} + \frac{g d_{eff}}{1 + g d_{eff}} R \quad (3)$$

A second type of static application that an active member can be applied to is as a force source, as illustrated by figure 3. An example of this type of application is the active athermalization of a truss structure (Salama, et al, 1993), which can arise in a segmented reflector development. Segmented reflectors require precise positioning and alignment of the reflector segments for coherent image formulation. The reflector segments that form the primary reflecting surface are mounted on a support structure. This structure can include in-line actuator elements that are used to change the shape of the base structure to assist with the reflector figure initialization and maintenance. Specifically, the active members can be used to actively athermalize selected support structure degrees of freedom. In general, the reflector support structure is a statically indeterminate truss. Therefore, any extension of one member is resisted by the other truss members. In this instance the force applied by the active member to the load, k_l , is

$$F = \frac{k_l k_{am}}{k_l + k_{am}} d_{eff} V \quad (4)$$

Now if a closed loop system were used to control the force applied by the active member the applied force is given by

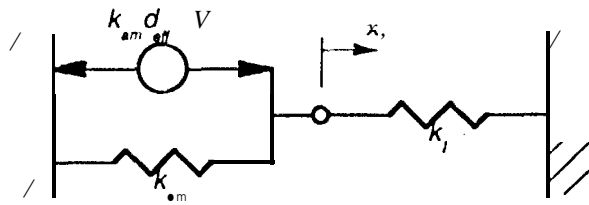


Figure 3: Ideal active member driving parallel stiffness.

$$F = k_{am} d_{eff} V - k_{am} x \quad (5)$$

Let

$$V = -g(F - R) \quad (6)$$

Therefore,

$$F = \frac{k_l k_{am}}{k_l + k_{am} + k_{am} k_l g d_{eff}} d_{eff} V \quad (7)$$

Typically, active members for shape control and large scale positioning will be different in design than the active members for vernier positioning and vibration control. Active members for shape control typically are required to have strokes of several millimeters, stalled force values in the hundreds of pounds, but low bandwidths. These design requirements are derived for a given operational scenario, for example in order to actively **athermalize** a structure, a temperature distribution is assumed, optimal actuator locations are chosen and then the required actuator stroke is found, the stalled force is determined by the required stroke and parallel structural stiffness. Given the shape control active member design requirements it is evident that either novel uses of an active material such as in an inch worm device or a moonie actuator and/or a mechanical mechanism such as a ballscrew may be a more appropriate actuator for coarse shape and positioning control.

Vibration Control

Vibration control or damping is important for some structures, particularly in the design of robust high gain controllers. Typically, damping increases control loop stability margins. Since the active member itself is inherently lightly damped, a local control loop is closed around the active member. The control strategy used here is to feedback the integral of the force produced by the active member, i.e.

$$V(s) = \frac{g}{s} F(s) = \frac{g}{s} (k_{am} d_{eff} V(s) - k_{am} X(s)) \quad (8)$$

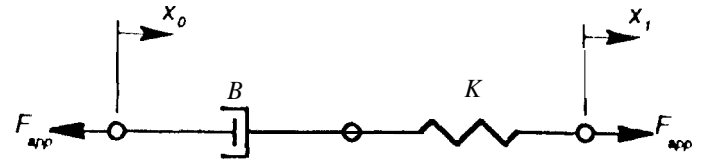


Figure 4: Damper and spring in series.

The resulting equation of motion for a system such as figure 2, is in the Laplace domain

$$m s^2 X(s) + \frac{k_{am} S}{s + g k_{am} d_{eff}} X(s) = 0 \quad (9)$$

If one considers the impedance of a spring and damper in series, shown in figure 4, one obtains

$$Z = \frac{sB + K}{KB} \quad (10)$$

By matching coefficients of the impedance in equation 10 and the inverted impedance multiplying the $sX(s)$ term in equation 9, one finds

$$K = k_{am} \quad (11)$$

$$B = \frac{1}{g d_{eff}} \quad (12)$$

Therefore, an active member using integral force feedback is **equivalent** to a spring and damper in series. Note that this arrangement does not have a static stiffness. This is alleviated in two ways: 1) the redundant nature of the structures that active members have been used in, and 2) the AC coupling of the load cells used to sense the active member force. When an active member with integral force feedback is used to damp a structure, the structure appears softer by virtue of small reduction in natural frequencies, see figure 5. The frequency response functions illustrated in figure 5, show a typical comparison of open and closed loop performance, see Umland and Chen (1992).

Experiments at JPL have also shown that very little stroke is needed for this application. Although the stroke required is dependent upon the magnitude of the structural excitation. These experiments have indicated that bandwidth of the actuator is the most important design parameter for this application. It is generally desirable that the bandwidth of the actuator be as broad as possible. The active member bandwidth is dependent on the driving electronics and the active member's material and physical properties. In the case of the electromechanical actuators described here, the driving

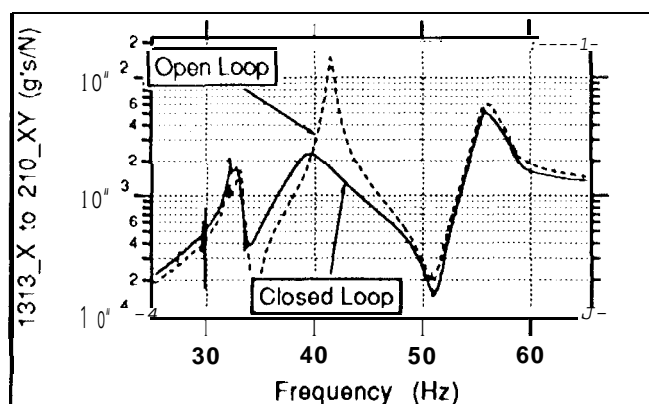


Figure S: Typical open and closed loop comparison.

hardware is the amplifier that supplies the command voltage or current. The bandwidth of the piezoelectric and electrostrictive active members plus electronic drive systems is influenced by the capacitance of the actuator structure. This is determined by the active material's dielectric constant and dimensions of the actuator. The bandwidth of the magnetostrictive actuator is determined by the mutual inductance of the actuator rod and coil, which also depends on the physical properties and dimensions of the rod. As improved power amplifiers have become available the active member system's bandwidth becomes limited by internal mechanical resonance's.

The second design requirement of importance is active member stiffness. Typically, the active member is designed to be at least as stiff, if not greater, than the struts that it will be used to replace.

Vibration Isolation

The model of figure 2 can also be used for isolation. Effectively, the actuator in figure 2 is used to adjust the active member's stiffness as desired. As in an earlier subsection, if position feedback is used, the active member's stiffness is adjusted according to

$$K = (1 + g d_{eff}) k_{am} \quad (13)$$

While if force feedback is used the active member spring stiffness is adjusted according to

$$K = \frac{1}{1 + g k_{am} d_{eff}} k_{am} \quad (14)$$

Note that, in each case negative feedback was assumed, therefore with a positive gain, g , position feedback tends to stiffen, and force feedback tends to soften,

The most important parameters here are stroke, stiffness and static strength. The stroke is determined by the size of the disturbance characteristics as a displacement. The stiffness should be as soft as possible, particularly for broadband disturbance isolation. The strength should be large enough that static loads are resisted and passed on to the structure. This is important in the case when the disturbance is a rigid body controller such as a momentum wheel,

Nonlinearity

All three materials discussed here have nonlinear material properties, although to date active material nonlinearities have not been a significant problem. Nonlinear behavior may degrade controller performance, particularly in high authority control. Controllers may be designed so that the nonlinearity of the material does not impact the performance of the closed loop control. An additional nonlinear effect that is more difficult to lessen the impact of is saturation of the actuator. This can lead to limit cycle instability in the control loop. Although this is a problem that is encountered in most closed loop systems.

III. ACTIVE MEMBER DESCRIPTION AND MODELING

There have been several active members designed and used by JPL for structural control. These active member designs listed in chronological order, are: (1) the Kaman Constant Length strut (Kaman, 1988), (2) the CSI second generation active member (Anderson, et al, 1990), (3) the PSR active member (Umland and Chen, 1992), (4) the ASTREX active member (Umland, 1992), and (5) the SatCon magnetostrictive active member (Johnson, 1992). The Kaman strut was developed by Kaman Aerospace Corp. in cooperation with JPL, and should be considered the first active member used at JPL. The Kaman CLS was used successfully for active vibration suppression of a number of laboratory test-bed structures, it also prompted several design modifications that are incorporated into the more recent designs. The CSI and PSR active members, see figures 6 and 7 respectively, were developed for these respective programs based upon experience gained from the Kaman strut. The ASTREX active member was developed by JPL for the ASTREX test-bed located at Edwards AFB, and is a variation of the CSI active member. The SatCon active member is a variation of the PSR design which uses a magnetostrictive actuator.

Each active member design is a variation on a common theme. Each design contains: (1) prime mover, (2) relative displacement sensor, (3) preload mechanism, and (4) axial motion mechanism. Later designs incorporate a pair of flex hinges, and an internal load cell. The prime mover is a generic term describing the solid state strain actuator used in the active

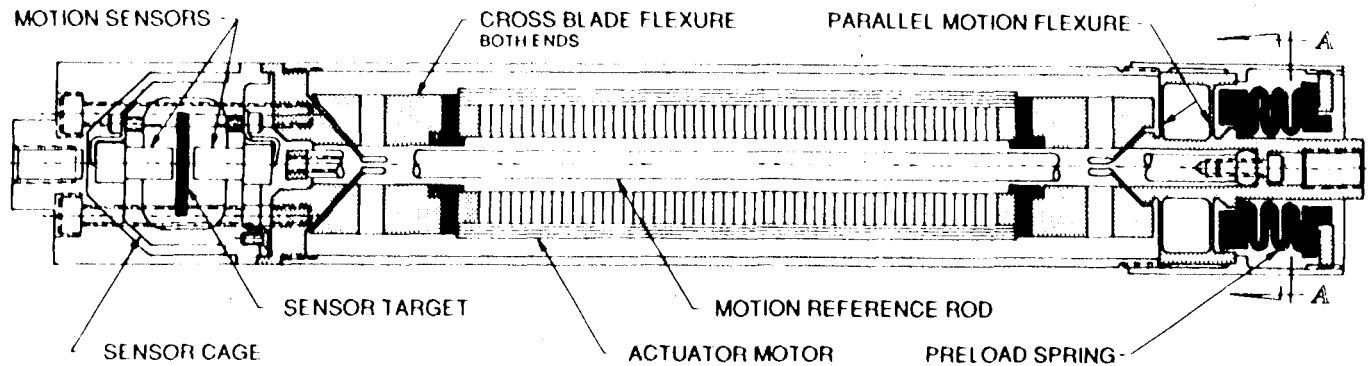


Figure 6: CSI active member

member. The three commonly available high bandwidth strain actuation materials, namely piezoelectric, electrostrictive, and magnetostrictive materials, have been used in the active member designs. These active materials are described in greater depth in a later section.

A displacement sensor is used in an active member to measure the output stem displacement, relative to the fixed end of the member. The sensor used in each case is the Kaman differential eddy current displacement transducer, model KDM-72001>. This sensor was chosen based on its (1) 1 nanometer resolution, (2) $\pm 0.9\text{mm}$ range, (3) high bandwidth, and (4) compact packaging. The differential transducer is used rather than the single ended version since it offers substantial performance improvements with minimal packaging modifications. The integration of the displacement sensor into the active member is where the CSI and PSR active members differ. The motion sensors in the CSI active member are fixed to the dead end of the member and sense the movement of the sensor target. The sensor target is attached to the output stem via a reference rod. The reference rod passes through the center of the member, therefore the internal active member parts must be cylindrical to allow the reference rod to pass. The PSR member, on the other hand, uses the case as the displacement sensor reference, and therefore the internal components do not require a central hole. The sensor target in the PSR member is fixed to a yoke which is integral to the output stem. The displacement sensors are then installed radially through a window in the casing.

From a conceptual view point, an active member is intended to replace any member in a truss. Hence, it must carry both tensile and compressive loads. It is also taken as a design rule that the multi-layer ceramics, that are used as the actuator motor, should never see tensile loads. Therefore, the actuator motor is preloaded by a preload spring and there are no positive connections to the motor that could transmit tensile forces should the preload be exceeded. That is, if a tensile force greater than the preload is applied, a gap will occur and the actuator motor will see zero force. A Belleville washer was

used in the Kaman CLS as the preload spring. Belleville washers have a stick-slip friction characteristic which is undesirable. The preload springs used in the both the CSI and PSR active members are designed to be zero stiction. The springs are cut from a monolithic piece of precipitation hardened stainless steel with the wire electrical discharge machining (EDM) process.

A parallel motion flexure supports the member's output stem. This flexure allows the stem to translate axially with zero friction even in the presence of side loads and bending moments. Cross blade flexures, also known as flex hinges, are located at both ends of the active motor such that the actuator is isolated from bending moments which can arise from externally applied loads, and fabrication tolerances.

The PSR piezoelectric and the ASTREX active members both incorporate a load cell which is internal to the member, rather than the external load cell used previously.

Detailed Active Member Model

A detailed active member model is illustrated in figure 8. The various stiffnesses are as follows: k_f is the crossblade flexure, k_{stack} is the actuator stack, k_p is the preload spring, and k_{stem} is the output stem. The effective displacement constant for the actuator stack is d_{stack} . These constants are related to the active member constants, k_{am} and d_{eff} , of figure 1 by

$$k_{am} = \frac{k_{stem}(k_{stack} k_f + 2 k_p k_{stack} + k_p k_f)}{2 k_{stack} k_{stem} + k_f k_{stem} + k_{stack} k_f + 2 k_p k_{stack} + k_p k_f} \quad (15)$$

$$d_{eff} = \frac{d_{stack}}{1 + \frac{2 k_p}{k_f} + \frac{k_p}{k_{stack}}} \quad (16)$$

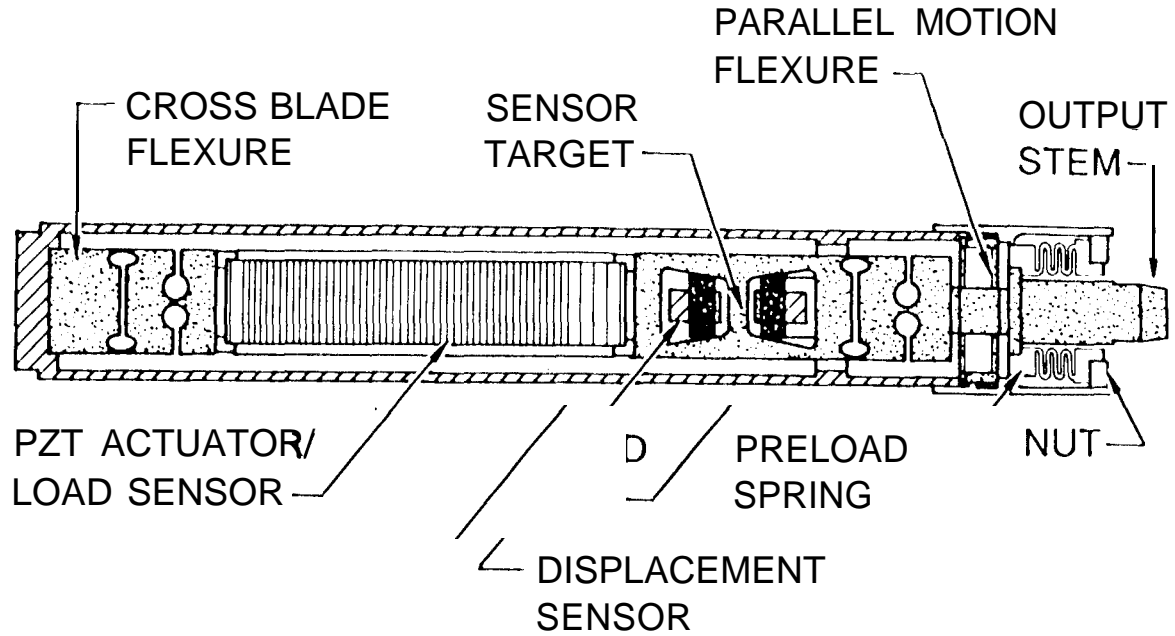


Figure 7: PSR active member

Equation (16) indicates an active member design rationale, i. e. the preload spring, k_p , must be made softer than both the actuator, k_{stack} , and the crossblade flexure, k_f . This is done such that the stack extension is not lost in compression of either the flexures or the stack,

IV. ACTUATOR MATERIAL CHARACTERISTICS

The properties of the actuator materials largely determine the properties of the in-line actuators. Piezoelectric and electrostrictive materials are similar in that they are electromechanical, a given amount of mechanical energy is produced for a given amount of electrical energy. There are differences in specific material properties that could impact design selection in certain applications, Magnetostrictives also produce mechanical energy from electrical energy. However this is accomplished through an electrically induced

magnetic field. This also has significant impact on design decisions.

Properties of Piezoelectrics and Electrostrictives

The relations necessary for an accurate description of induced strain actuation in piezoceramics include an electrical relation, a mechanical relation, and a coupling term. For piezoceramic materials such as lead zirconate titanate (PZT), the constitutive relations are (Nye, 1985)

$$x_{ij} = s_{ijkl}^E X_{kl} + d_{ijk} E_k \quad (17)$$

$$D_i = d_{ijk} X_{jk} + \epsilon_{ij}^X E_j \quad (18)$$

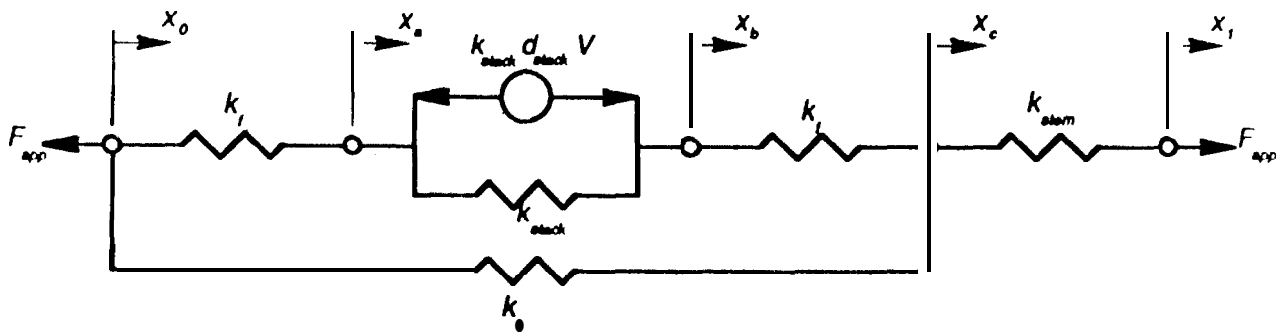


Figure 8: Detailed active member model.

x_{ij} represents the elastic strain tensor, X_{kl} is the stress tensor, E_k is the electric field vector, and D_i is the dielectric displacement vector. The coefficients s_{ijkl}^E and ϵ_{ij}^X are the components of the elastic compliance tensor measured at constant electric field, and the dielectric permittivity tensor measured at constant stress, respectively. The components d_{ijk} of the piezoelectric tensor describe the linear electromechanical coupling.

For applications which require either large displacements or a desired stiffness and still deliver full displacement at reasonable voltage levels a stack can be made from layers of piezoceramic material. The PZT material in such a stack is mechanically in series and electrically in parallel. The displacement of the stack is equal to the sum of the displacements of the individual ceramic elements. Typically, the d_{33} coefficient of the piezoelectric tensor is exploited in a stack design. The d_{33} coupling coefficient represents the strain along the ceramic's poling direction when a field is applied in this direction. The d_{33} term is larger and hence a more effective electromechanical coupling than the transverse coefficient, d_{31} . Based on (17) a stress-free actuator will deliver a displacement of

$$\Delta l = Nd_{33}V = d_{eff}V \quad (19)$$

Therefore,

$$d_{eff} = Nd_{33} \quad (20)$$

Where N is the number of wafers and V the applied voltage. The difference between high voltage and low voltage actuators lies in the thickness of the wafer and therefore in the number of wafers N. A larger number of thinner wafers allows a smaller V to attain the same stroke. d_{eff} is the effective piezoelectric gain of the stack. The capacitance of a stacked actuator consisting of N wafers which are electrically in parallel is given by

$$C = \frac{N\epsilon A}{y} \quad (21)$$

Note that, the capacitance of the stack is proportional to the number and inversely proportional to the thickness of the wafers. The capacitance of a low voltage piezoelectric stack increases quadratically, in comparison to a similar high voltage stack.

Electrostriction is the dependence of the state of strain of a ferroelectric material proportional to the even powers of the applied electric field. The **electrostrictive effect** is mainly

second order such that the sign of the deformation is independent of the polarity of the applied field. Electrostriction is a universal property of all dielectrics but can only be observed in materials with high dielectric coefficients. Lead magnesium niobate (PMN) is one electrostrictive material that has been used as a solid state actuator. The constitutive relation analogous to (17) for electrostrictives is (Nye, 1985)

$$x_{ij} = s_{ijkl}^E X_{kl} + d_{ijk} E_k + m_{kij} E_k E_l \quad (22)$$

where the only difference is the additional quadratic dependence of strain on electric field. A stacked electrostrictive actuator using m_{33} will deliver a displacement of

$$\Delta l = Nm_{33} \frac{V^2}{t} \quad (23)$$

The effective strain coefficient in terms of the electrostriction coefficient is by definition

$$d_{33} = \left(\frac{\delta S_3}{\delta E_3} \right)_T = 2 m_{33} E_3 \quad (24)$$

that is, the strain per field is increasing linearly with field. Equation (6) allows one to calculate an effective actuator stack gain about an electrical bias point, i. e.

$$d_{eff} = N d_{33} \Big|_{bias} \quad (25)$$

Typical PZT and PMN materials exhibit high stiffness and can provide essentially constant gain (mechanical output/electrical input) for a given field up to several kHz. Neither material is, however, accurately modeled by a single constant coefficient d_{33} or m_{33} . The d_{33} and m_{33} coefficients actually change as the dielectric coefficient is altered with increased mechanical deformation. The dependence of the piezoelectric strain coefficient d on strain is particularly troublesome in piezoceramics. Not only does the dielectric coefficient change in magnitude (typically increasing by a factor of 2 over an actuator operating range), but the dielectric loss tangent can be as high as 20-30%. This loss tangent increases with higher strains. Thus, the effective displacement per volt from a piezoceramic actuator stack will change (increase) at larger mechanical displacements. In addition, the relation is increasingly hysteretic with amplitude. Closely related to hysteresis is the phenomenon of piezoelectric creep. The step response of a piezoelectric actuator to an applied field will show an increasing displacement over time. Aging of piezoceramics also occurs, leading to a slow degradation of

properties. In addition, the lossy dielectric coefficient causes piezoelectric actuators to suffer from capacitive heating, a phenomenon which becomes increasingly important as the frequency of operation is increased.

Electrostrictives also have a variable dielectric coefficient, which, however, decreases with strain, causing strain which is less than quadratic with field. The departure from quadratic behavior is often beneficial, since the field-strain relation "turns over" and creates a sizable nearly-linear region. Loss tangents are typically low (near 1%), implying low hysteresis, negligible creep, and little aging. Because of their high dielectric coefficients (near 20,000 compared to 1500 for a typical piezoceramic), electrostrictive actuators have higher capacitance's, implying lower actuator bandwidth for a fixed current. Capacitive heating is, however, greatly reduced.

Properties of Magnetostrictive Materials

Magnetostriction describes the property of materials that causes them to strain when in the presence of a magnetic field. This property can be used for actuation by varying the magnetic field through the combined use of permanent magnets a current driven through a coil. This effect is present in many different materials. Terfenol-D, developed at Ames Laboratory is an alloy of the rare earth elements terbium and dysprosium plus iron. It produces high strain without the requirement of large magnetic fields. ETREMA Terfenol-D® is commercially produced by Edge Technologies, Inc. under license through Iowa State University and the United States Navy. For typical room temperature applications, Terfenol-D actuators use material with stoichiometry $Tb_yDy_{(1-y)}Fe_2$, directionally solidified into a near single crystal by a variety of techniques,

The complicated physics of the magnetostrictive precludes the derivation of an simple, accurate equation relating the electric current applied to the magnetically-induced strain of the actuator. In a very rudimentary sense though, the behavior of the magnetostrictive material is described by the constitutive equations (Butler, 1988)

$$x_{ij} = s_{ijkl}^H X_{kl} + d_{ijk} H_k \quad (26)$$

$$B_i = d_{ijk} X_{jk} + \mu_{ij}^X H_j \quad (27)$$

Where the vectors B_i and H_k represent the flux density and the magnetic field respectively. The behavior of the actuator is more effectively summarized experimentally by finding the stress-strain-magnetizing field relation for the material. One view of this relation, for room temperature Terfenol-D, is shown in figure 9. Shown are curves of magnetostriction,

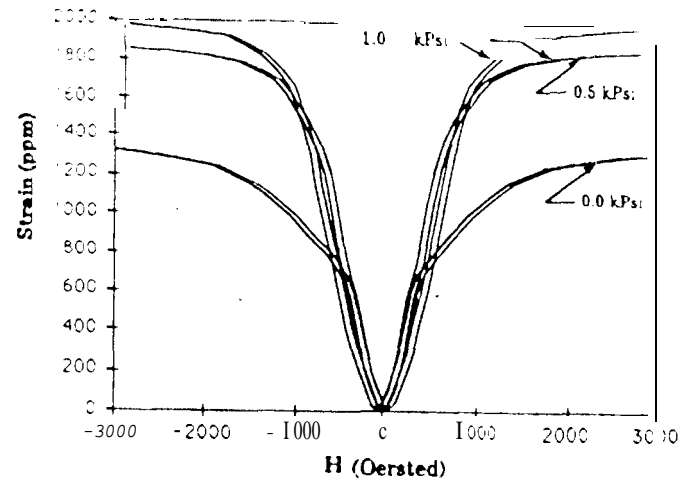


Figure 9: Terfenol magnetostriction.

measured in parts per million (microstrain), versus applied magnetizing field H , measured in Oersteds, for various compressive stress levels in the material. The magnetostriction in Terfenol-D causes the material to increase in length when the magnetizing field is applied parallel to the material drive axis. As can be seen in the figure, strains of over one thousand microstrain are possible. Another important property is that the magnetostrictive performance improves dramatically if the material is under compressive stress.

As can be seen by the symmetry of the curves, the magnetostrictive strain depends only on the magnitude of the applied magnetizing field, not its sign. For actuator applications, the material is usually magnetically biased, typically with permanent magnets. This has a number of desirable effects. The first is that the actuator becomes bidirectional about the bias strain, Actuator linearity and gain are also improved.

The curves in figure 9 were gathered by driving the Terfenol-D material with low frequency sinusoids in current, resulting in sinusoidal magnetizing field. As can be seen, the resulting strain shows a moderate level of hysteresis. This hysteresis is dominated by the normal ferromagnetic hysteresis between magnetizing field and resulting magnetic field. The effect of this hysteresis on closed-loop control can be significantly reduced by using the magnetic field feedback in the actuator drive electronics (Johnson, et al, 1992). The significant nonlinearity between the material input (magnetizing field produced coil currents) to strain must be accounted for in the active member electronics design. Approaches include using high band-width force or displacement feedback, limiting material strains to the most linear region, or using feedforward nonlinear compensation,

Commercial Terfenol-D is a near single-crystal material, but a metallic crystal, not a ceramic. It is relatively brittle, compared to most metals, and can be fractured if subject to

Table 1: Active Member Characteristics

Active Member Design	Material	$\delta F=0$ @ Exc. (pm)	C (μF)	L (mH)	K _{short} (lb/mil)	M (g)	BW (kHz)
JPL CSI	HV PZT	63.4 @ 1000V	0.6	N/A	83.6	240	0.4
JPL CSI	LV PZT	45 @ 100V	11	N/A	85.6	229	2
JPL CSI	PMN	39.5 @ 150V	7.6	N/A	55.7	190	N/A
JPL PSR	LV PZT	45 @ 150V	22	N/A	118	350	2
SatCon PSR	Terfenol-D	65 @ 4 Amps	N/A	5-10	89	480	N/A
Kaman	Hv PZT	54 @ 1000V	0.5	N/A	150	365	0.4

moderate tension or impact-type forces. Its durability in this regard is improved when placed under compressive pre-load, which also improves performance, as discussed above. Because of its metallic crystalline nature, no known fatigue mechanisms exist. In particular, it is not susceptible to treeing-type fatigue failures that are found in ceramic materials.

V. ACTIVE MEMBER CHARACTERIZATION

Table 1 lists test data for a number of active members. Column one indicates the active member design type, i. e. CSI, PSR, or Kaman. Column two indicates the active material used, i. e. piezoelectric (PZT), electrostrictive (PMN), or magnetostrictive (Terfenol-D). The piezoelectric class is further distinguished as high voltage (HV), or low voltage (LV). Columns three through six indicate active member characteristics, including: no load deflection ($\delta F=0$) for a given excitation; capacitance (C); inductance (L); short circuit stiffness (K_{short}); mass (m); and bandwidth (BW).

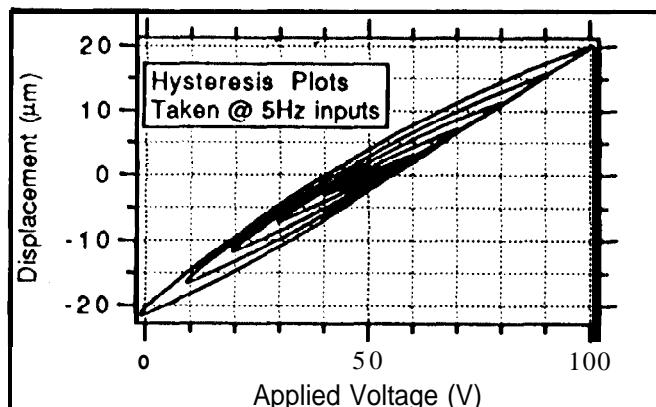


Figure 10: Piezoelectric active member displacement curve.

Figures 10 through 12 illustrate typical displacement versus excitation curves for piezoelectric, electrostrictive, and magnetostrictive active members, respectively. These curves are representative of the different material types.

The piezoelectric active member of figure 10 tends to be linear with hysteresis. The slope of the hysteresis curves is the active member's effective displacement constant. This constant tends to increase with driving amplitude and decrease with driving frequency. The level of hysteresis also tends to increase with driving amplitude. Note that the piezoelectric active member is driven only with positive voltage. If the piezoelectric is driven with excessive voltage of negative polarity the piezoelectric material will depole.

The characteristic displacement curve for the electrostrictive active member is shown in figure 11. The electrostrictive active member displays minimal hysteresis, and whose shape deviates from the expected quadratic behavior at higher voltages. The electrostrictive actuator can be driven with negative voltage, there is no danger of depoling, since

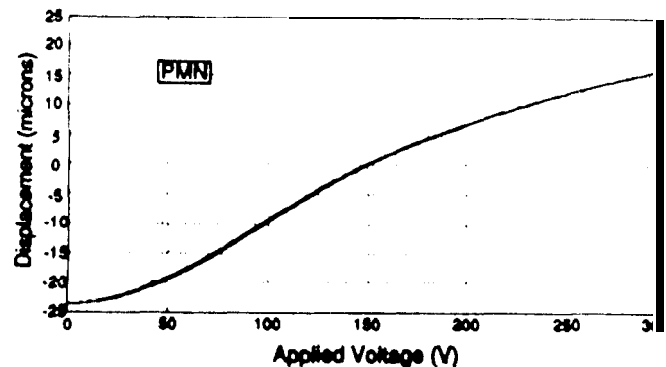


Figure 11: Electrostrictive active member displacement curve (Anderson, et al, 1990).

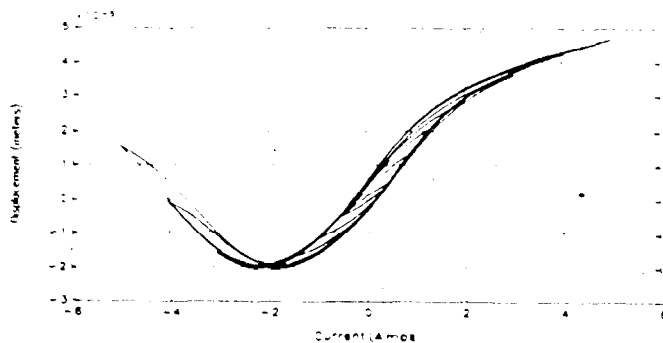


Figure 12: Magnetostrictive active member displacement curve (Johnson, et al, 1992)

the material does not have to be poled,

The behavior of the magnetostrictive active member is illustrated in figure 12. Note that the excitation is current not voltage. The magnetostrictive material displays about the same level of hysteresis as the piezoelectric. These curves illustrate a fundamental characteristic of the magnetostrictive material. In order for an active member to exhibit apparent bi-directional motion the active material must be biased. That is each of the active materials are only used as extensional actuators. Therefore the piezoelectric and electrostrictive actuators are biased with voltage, while the magnetostrictive actuators are biased with permanent magnets. Although, the magnetostrictive actuator could also be biased with current. Thus the magnetostrictive active member can be driven with bi-directional current and display bi-directional motion.

A typical active member transfer function between the actuator input and the displacement sensor is shown in figure 13. This transfer function indicates that the dominant mode of the actuator occurs at about 2.7 kHz. This mode is measured with the stem free. It consists of the stack and flexures oscillating against the preload spring. This transfer function is typical for all active members tested. The mode at 600 Hz is due to the motion sensor cage-and reference rod.

VI. SUMMARY

In this paper the use, design, modeling and characterization of active members for structural control was discussed. Test data was given which was illustrative of the performance of each of the three types of solid state actuation. At this point it is inappropriate to deem one material superior to another, since this type of selection must be application driven. Additionally, what has not been studied is the important costs of power and mass, which should also include drive electronics.

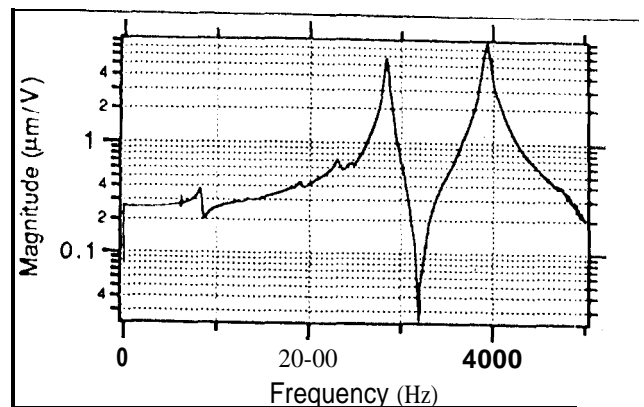


Figure 13: Typical active member frequency response function.

VII. ACKNOWLEDGMENTS

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